Deformable Registration and Tract-Specific Analysis of Diffusion-Weighted MRI

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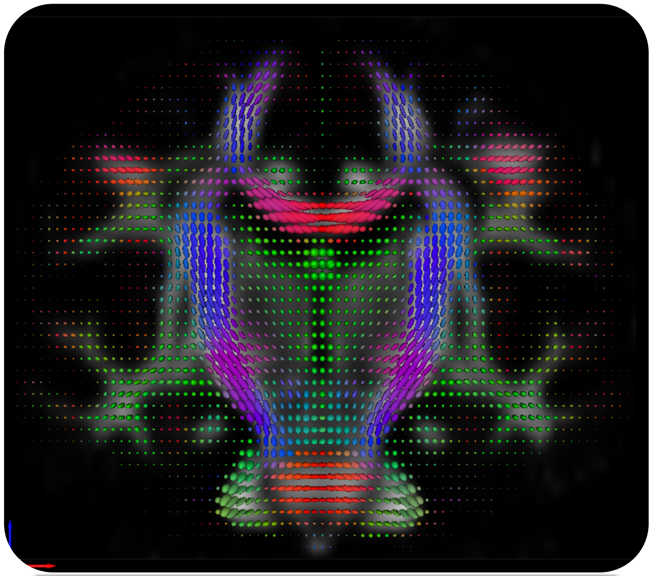
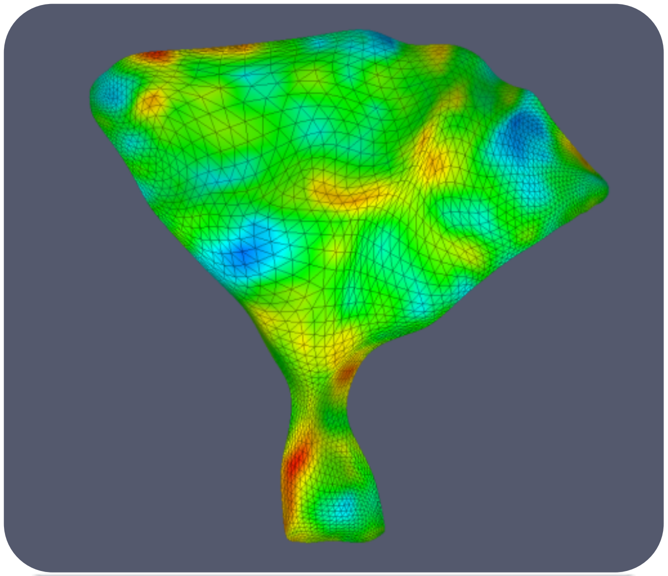
Outline



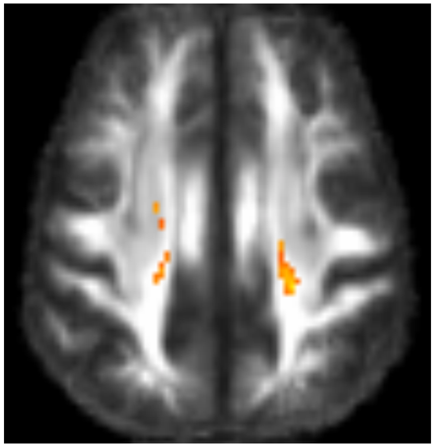
High-dimensional deformable registration of DW-MRI with DTI-TK



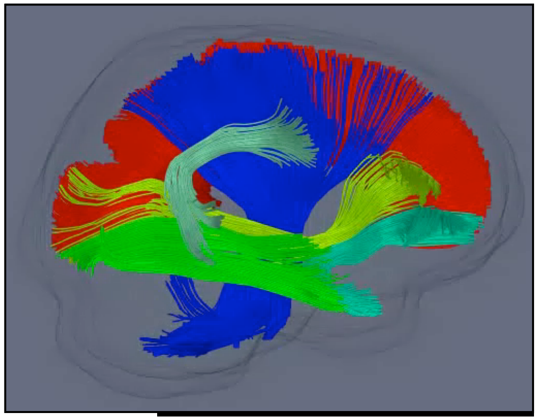
Framework for DW-MRI analysis via a surface representation of white matter tracts

Why spatial normalization?

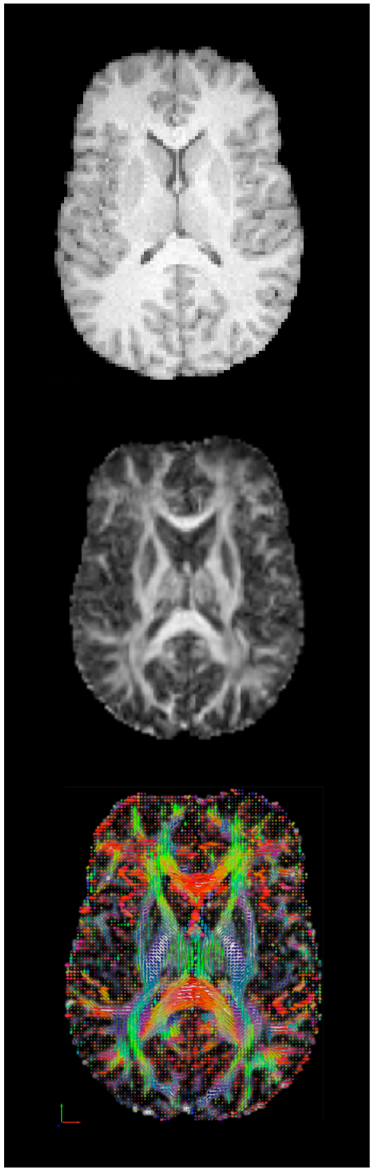
- Characterize disease effects on white matter
  - Deformation-based morphometry
  - Voxel-based morphometry



- Create white matter atlases
  - Study average anatomy, variability in anatomy, changes over time
  - Enable more robust fiber tractography

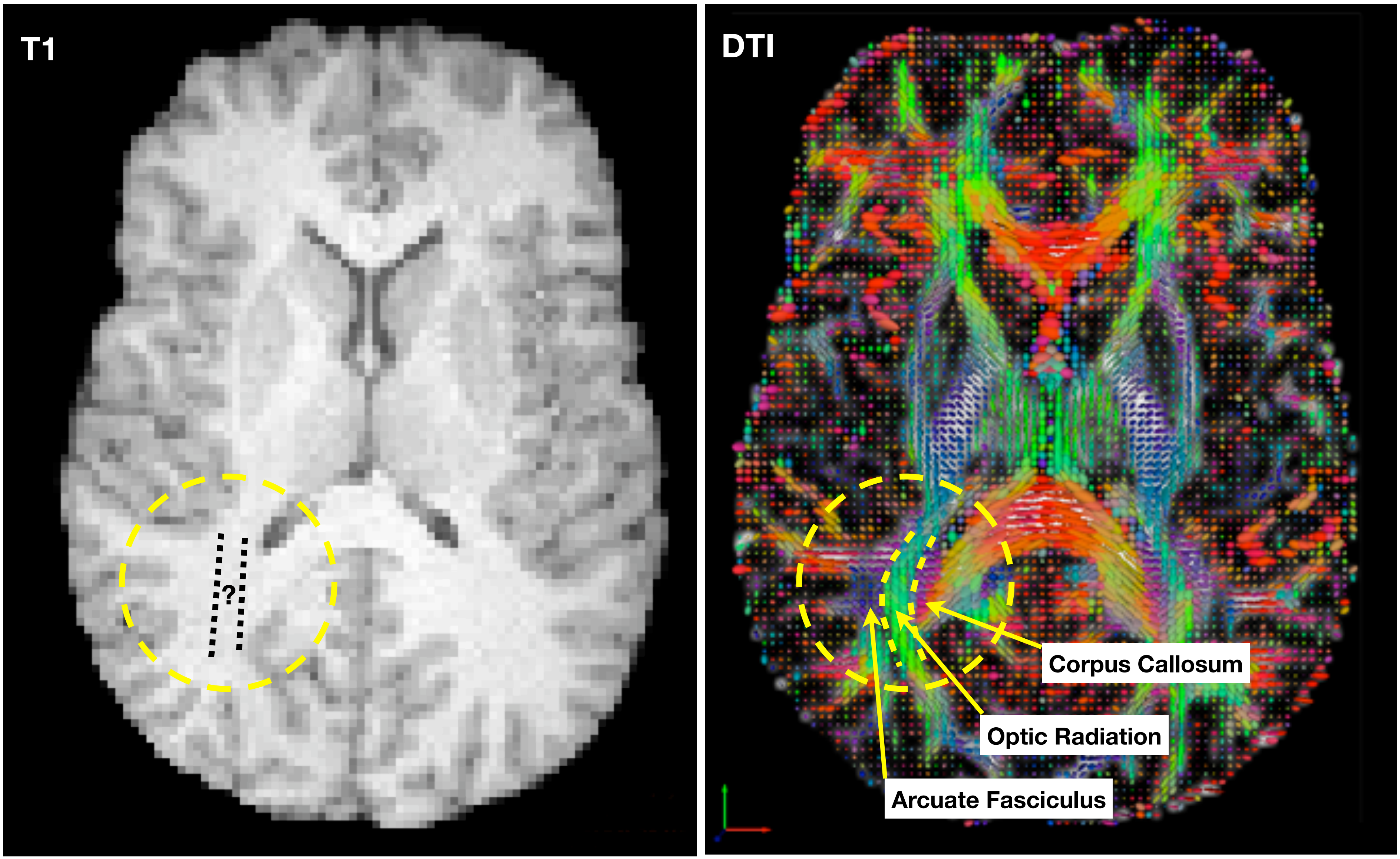


Registration of diffusion tensor images

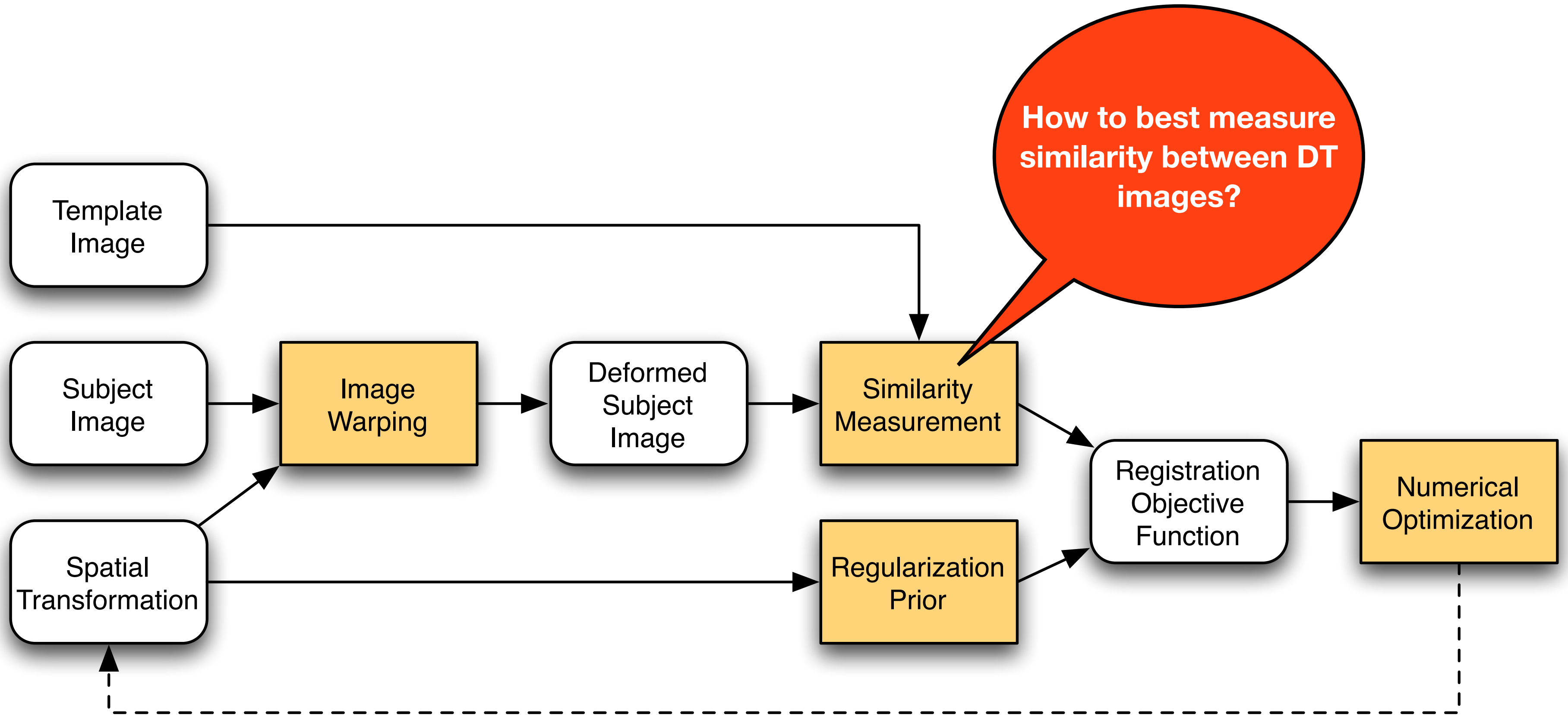


- Registering the corresponding T1 images
  - Xu et al, MRM 03
- Registering the DTI-derived FA images
  - Jones et al, NeuroImage 02
  - Andersson et al, FMIRB technical report 07
- Registering the tensor images themselves
  - Alexander et al, CVIU 00
  - Park et al, NeuroImage 03
  - Zhang et al, MedIA 06
  - Van Hecke et al, IEEE TMI 07
  - Yeo et al, IEEE TMI 09

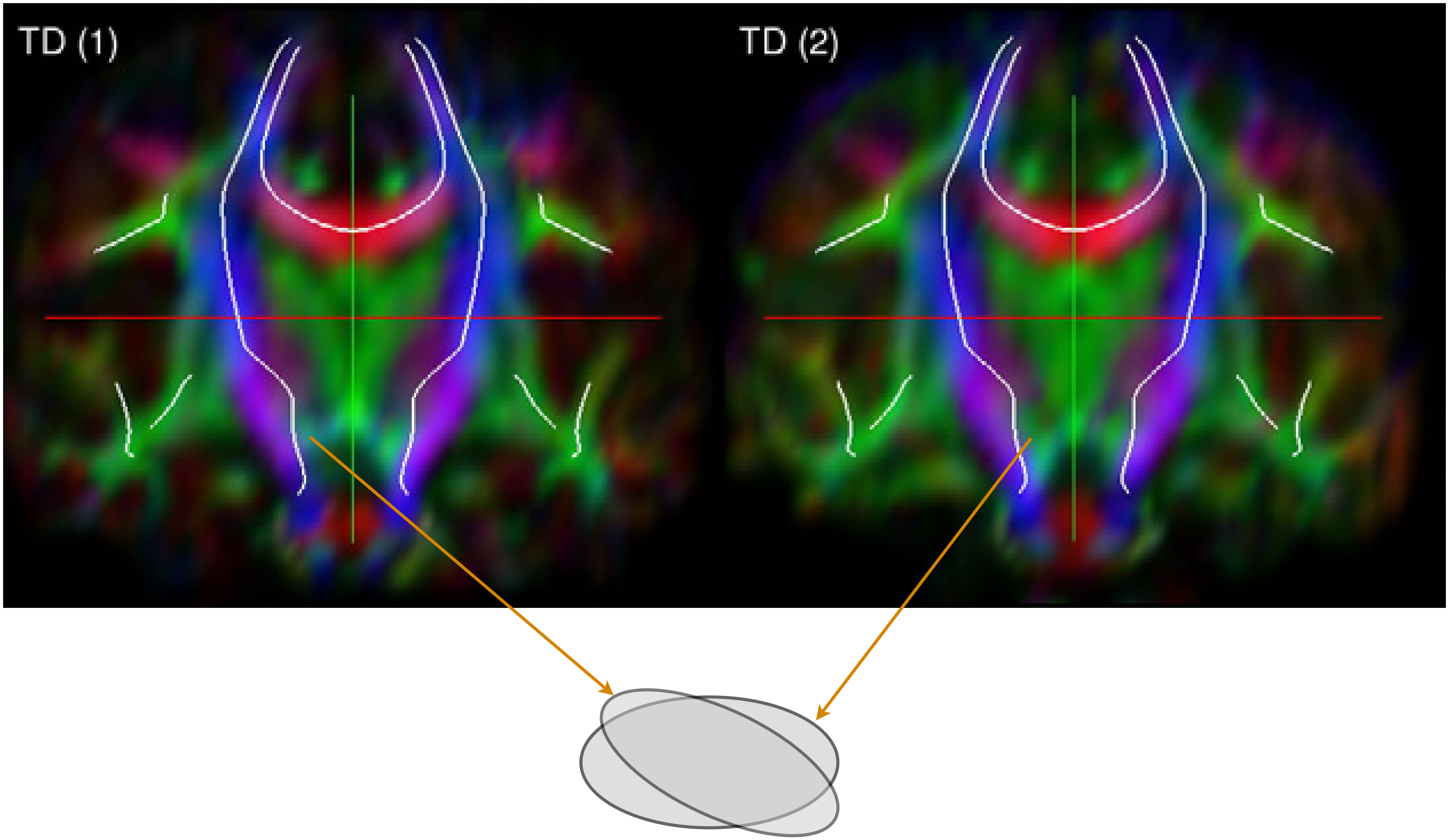
Diffusion-tensor imaging (DTI) reveals the organization of white matter



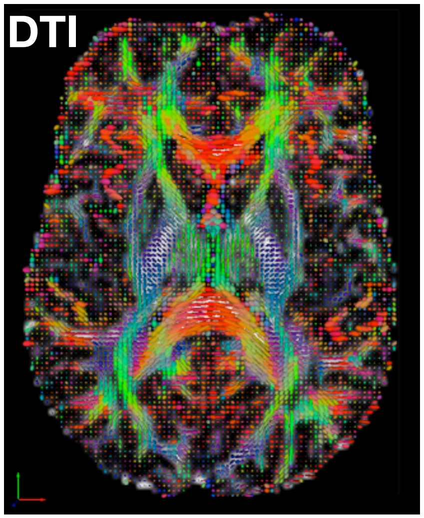
But how can image registration algorithms be adapted to DTI data?



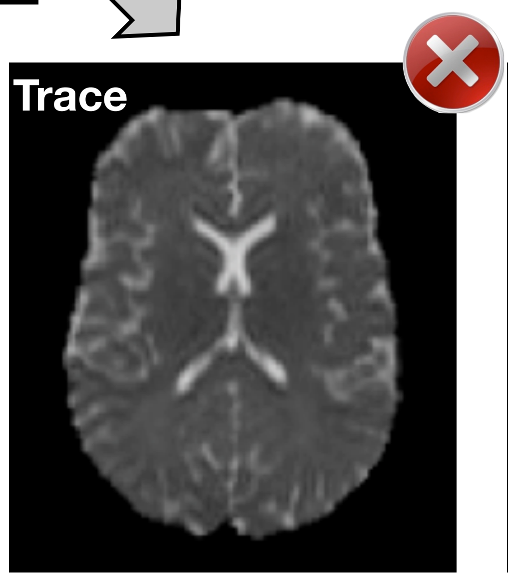
Measuring similarity between two DT images

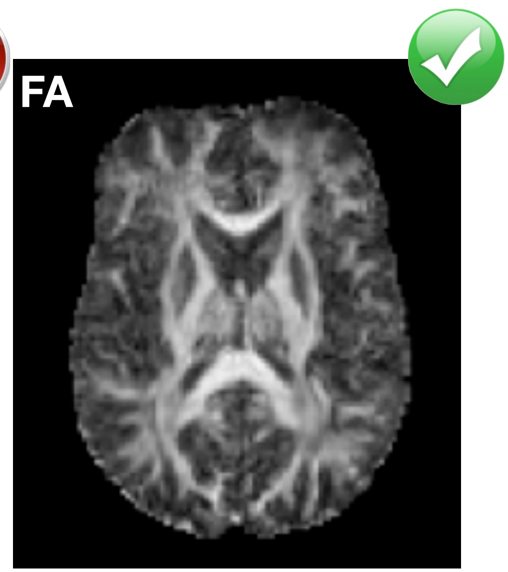


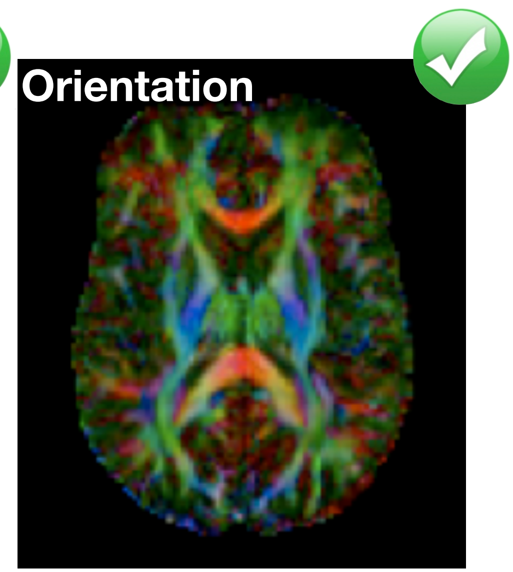
What properties of the diffusion tensor should use for image matching?



Pierpaoli et al., 1996: No significant differences in trace between white matter regions







DTI-TK tensor metric:
Euclidean distance between "deviatoric" tensors

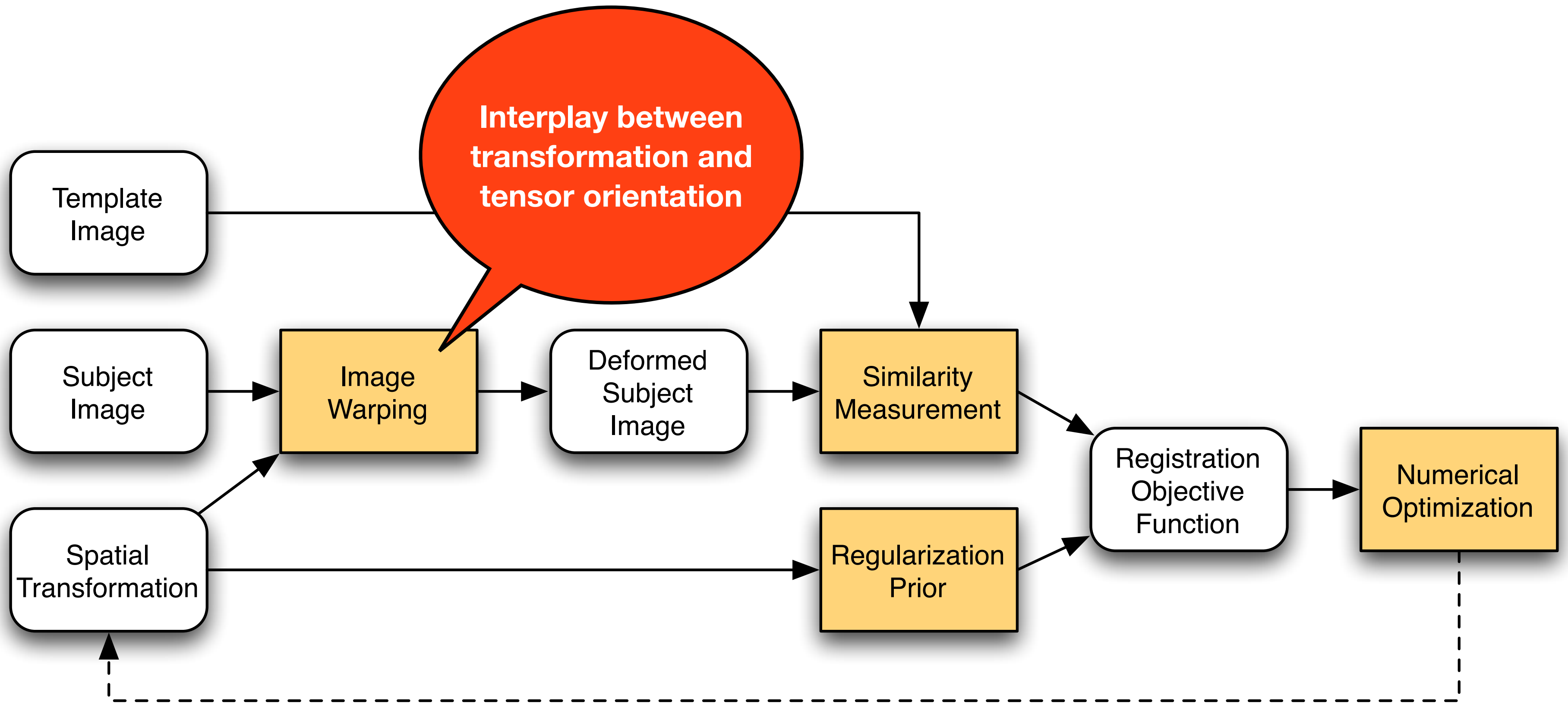
Tensor similarity:

$$\mu(\mathbf{D}_1, \mathbf{D}_2) \triangleq \sqrt{\mathrm{Tr}\left[\left(\hat{\mathbf{D}}_1 - \hat{\mathbf{D}}_2\right)^2\right]}$$

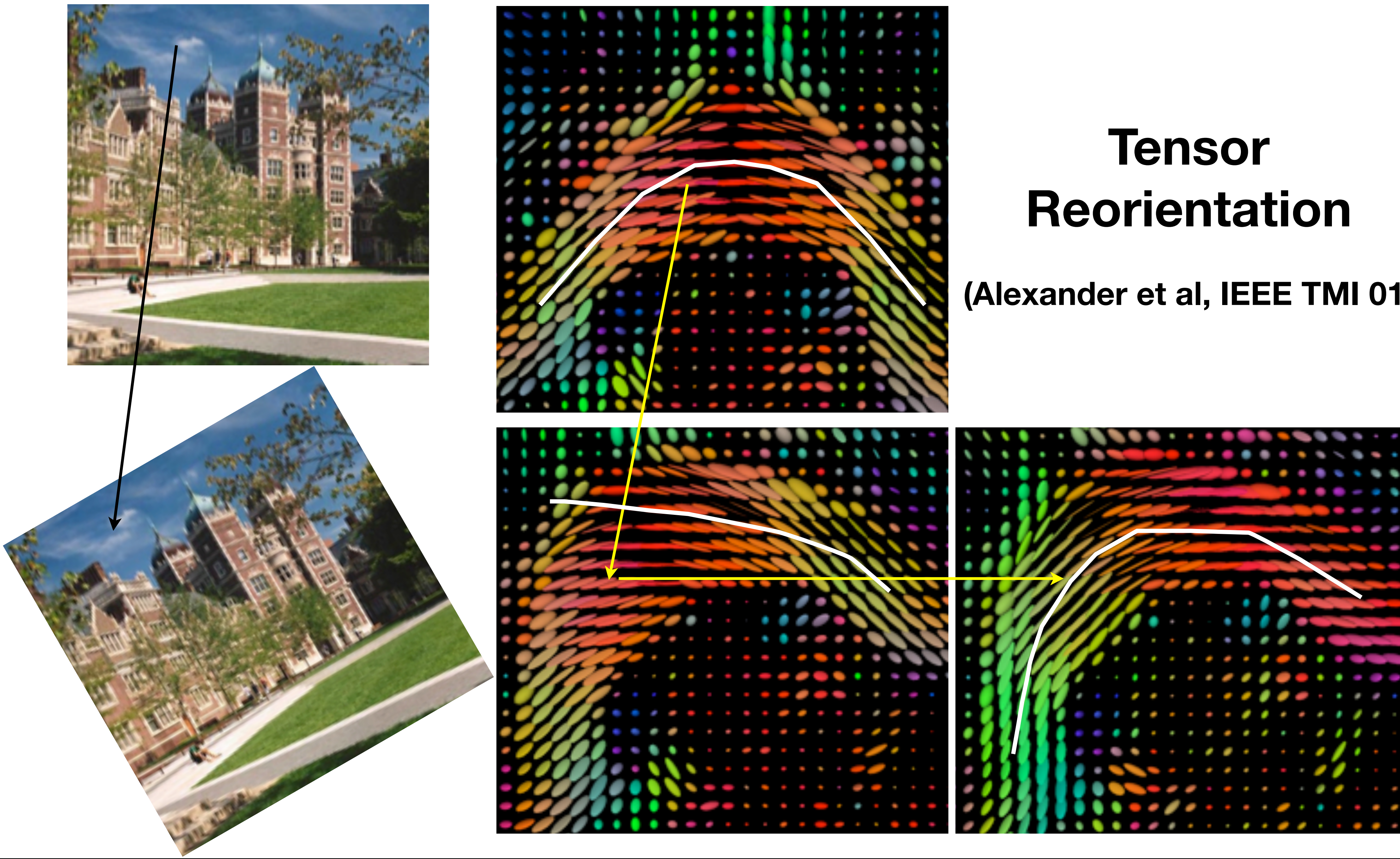
Deviatoric tensor:

$$\hat{\mathbf{D}} \triangleq \mathbf{D} - \frac{1}{3}\mathrm{Tr}(\mathbf{D}) \cdot I_{3\times 3}$$

But how can image registration algorithms be adapted to DTI data?



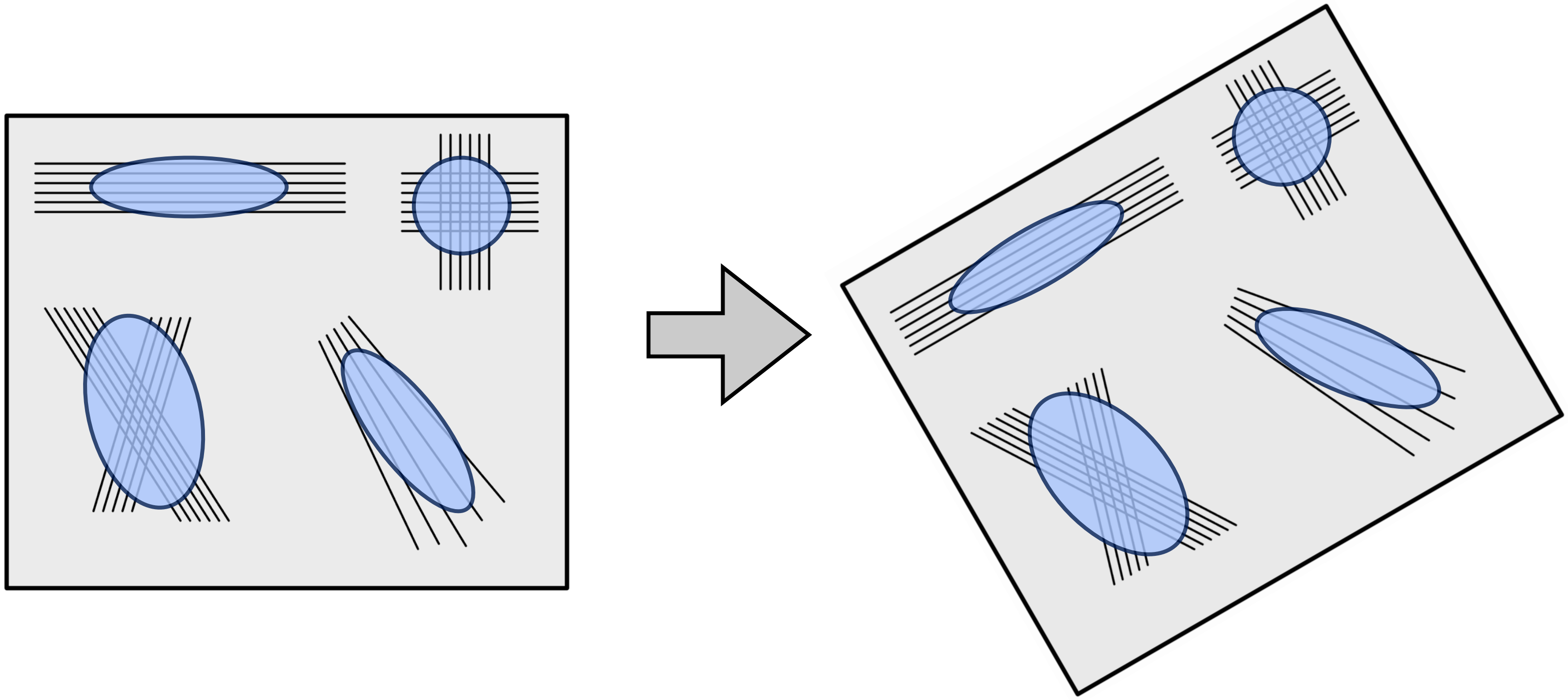
Treating DTI as “multi-channel” images results in nonsensical spatial transformations



Tensor Reorientation

(Alexander et al, IEEE TMI 01)

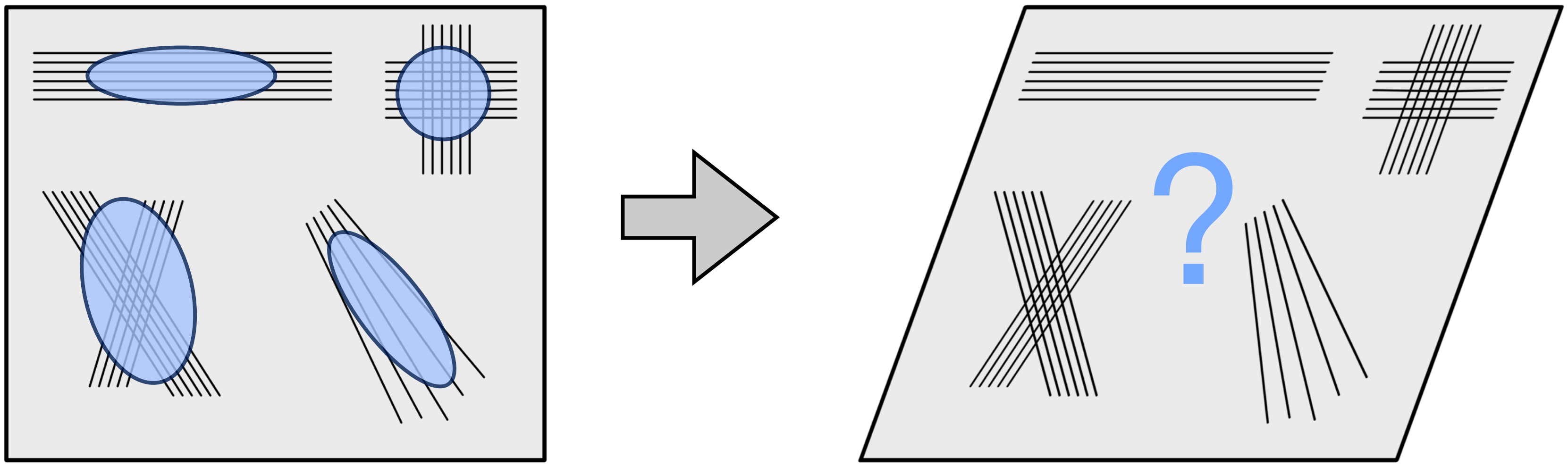
Tensor reorientation: **rigid** transformation case



$$\phi(\mathbf{x}) = Q\mathbf{x} + T$$

$$\mathbf{D}' = Q\mathbf{D}Q^{\mathrm{T}}$$

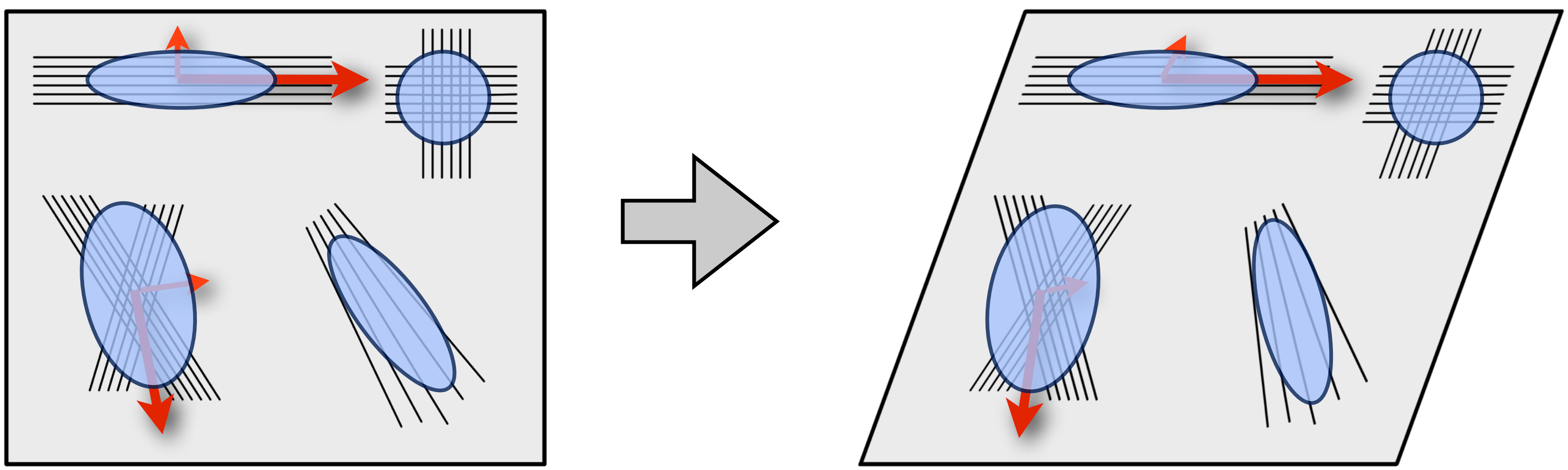
Tensor reorientation: **non-rigid** transformation case



$$\phi(\mathbf{x}) = M\mathbf{x} + T$$

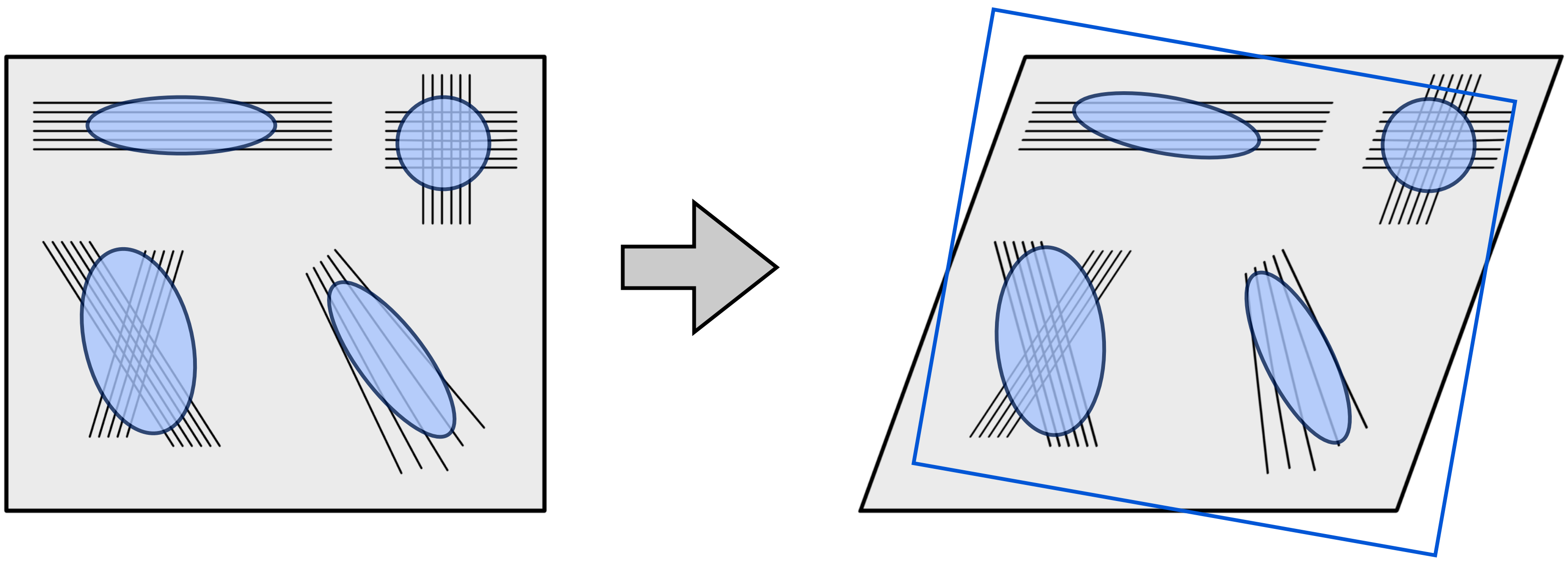
$$\cancel{\mathbf{D}' = M\mathbf{D}M^{\mathrm{T}}}$$

Tensor reorientation:
preservation of principal direction



Reorient tensor $\mathbf{D}' = Q\mathbf{D}Q^{\mathrm{T}}$ such that $\vec{e}'_1$, the principal eigenvector of $\mathbf{D}'$, coincides with $M\vec{e}_1$

Tensor reorientation:
finite strain

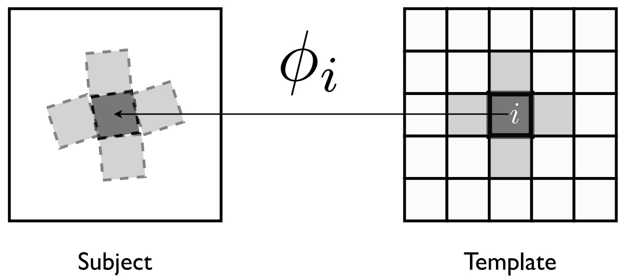


Reorient with rotation matrix Q that is the closest approximation of M

$$Q^* = \arg\min_{Q} \|Q - M\|$$

Efficient implementation of finite strain reorientation in DTI-TK

- Deformable transformation modeled as piecewise affine deformation



- Affine transforms modeled via polar decomposition as pure rotation (Q) and shape matrix (S):

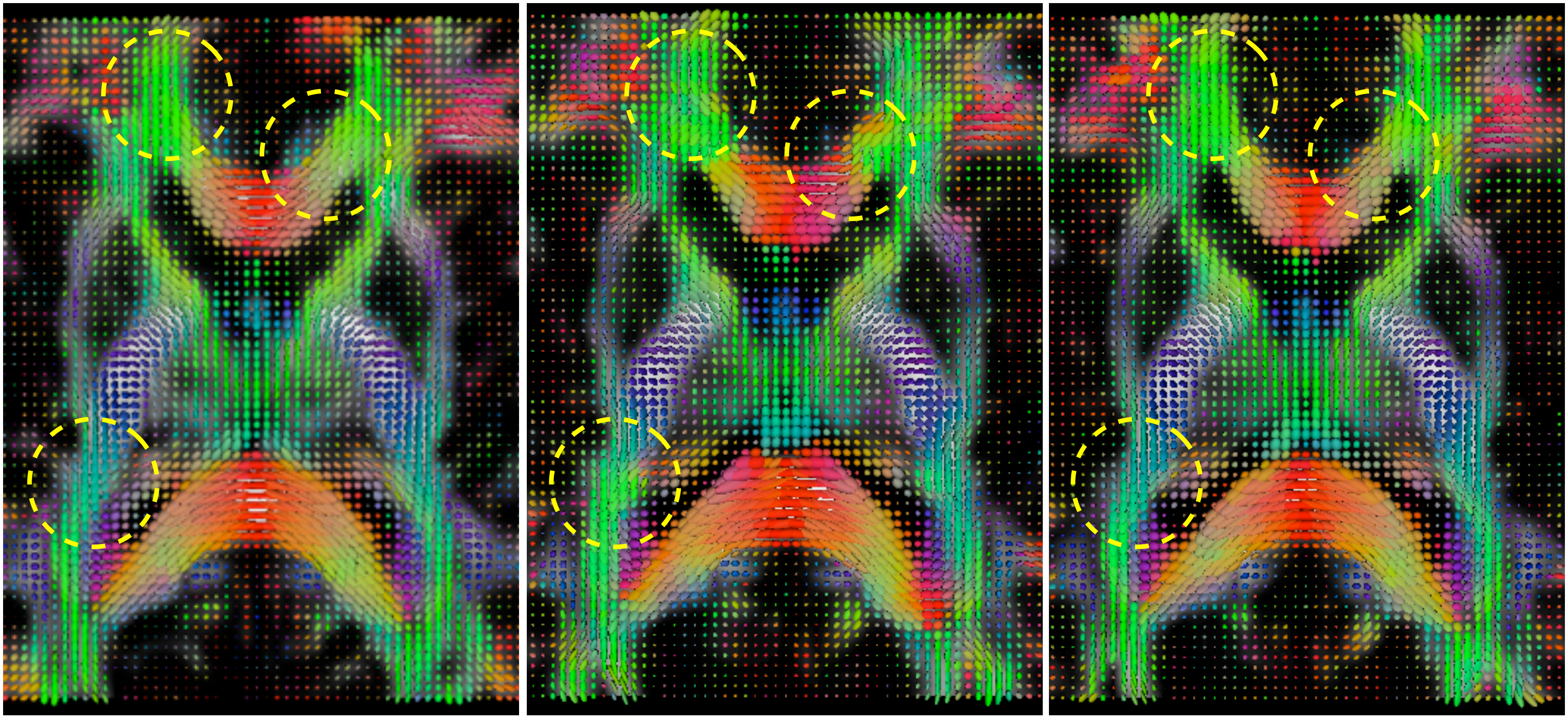
$$\phi_i(\mathbf{x}) = M_i\mathbf{x} + T_i \qquad M_i = Q_i S_i$$

Q is the finite strain solution!

- Overall objective:

$$\underset{\{Q,S,T\}_i}{\arg\min} \sum_{i=1}^{N} \int_{\Omega_i} \mu\left[\mathbf{D}_{\mathrm{s}}(\phi_i(\mathbf{x})), Q_i \mathbf{D}_{\mathrm{t}}(\mathbf{x}) Q_i^{\mathrm{T}}\right] \mathrm{d}\mathbf{x} \; + \; E_{\mathrm{reg}}(\phi_1, \ldots, \phi_N)$$

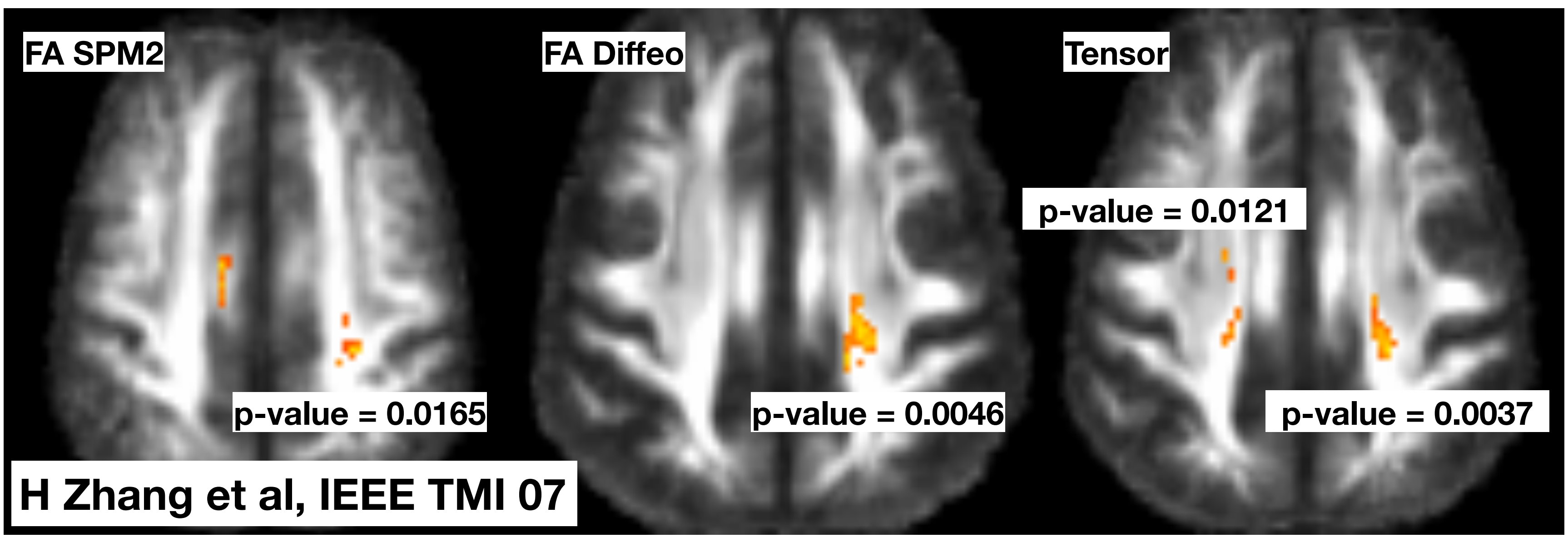
Improved tensor orientation alignment with tensor-based normalization



Template image (Target) | **FA-based normalization (Without Orientation)** | **Tensor-based normalization (With orientation)**

Tensor-based normalization improves the sensitivity of the detection of FA differences in ALS

- Task-driven evaluation of three normalization approaches
  - White matter changes in ALS as measured by FA
  - Cross-sectional design with 8 controls and 8 patients
- Key findings
  - Increased sensitivity of detected FA changes with tensor-based approach
  - Reduced susceptibility to false-positives due to shape confounds

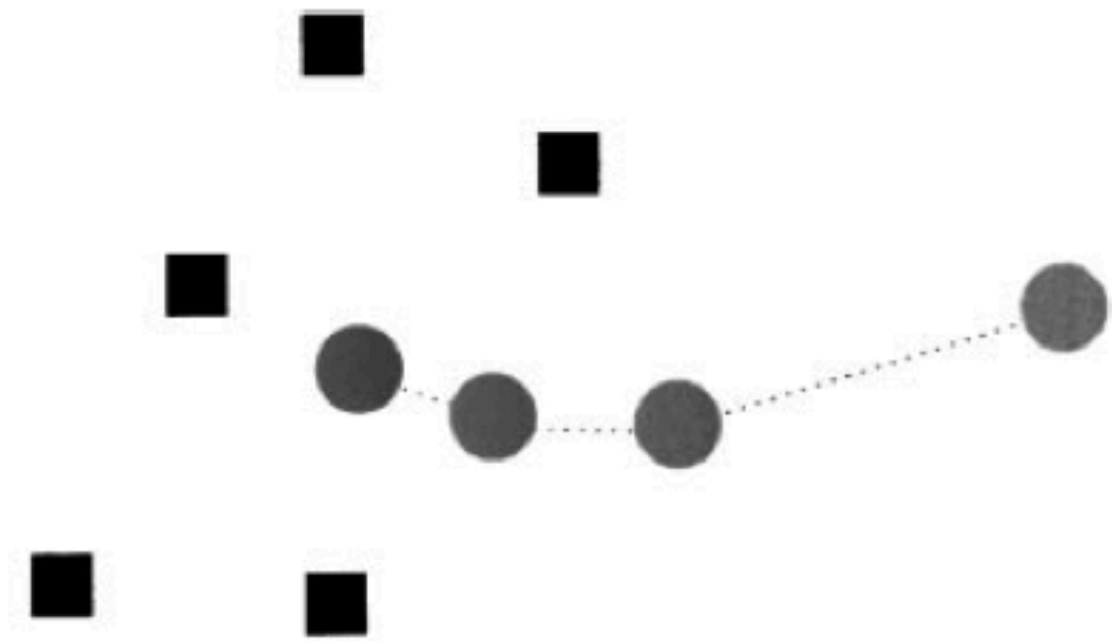


First systematic comparison of publicly available DTI registration tools (Wang et al, NeuroImage 11)

- FA-based registration tools
  - IRTK (Schnabel et al, MICCAI 01)
  - FNIRT (Andersson et al, FMRIB technical report 07)
  - Demons (Vercauteren et al, IPMI 07)
  - Log Demons (Vercauteren et al, MICCAI 08)
  - Fluid (Joshi et al, NeuroImage 04)
- Tensor-based registration tools
  - DTI-TK (H Zhang et al, MedIA 06)
  - MedINRIA (Yeo et al, IEEE TMI 09)

DTI-TK reported as top performer for the authors' application

Constructing population-specific white matter atlases

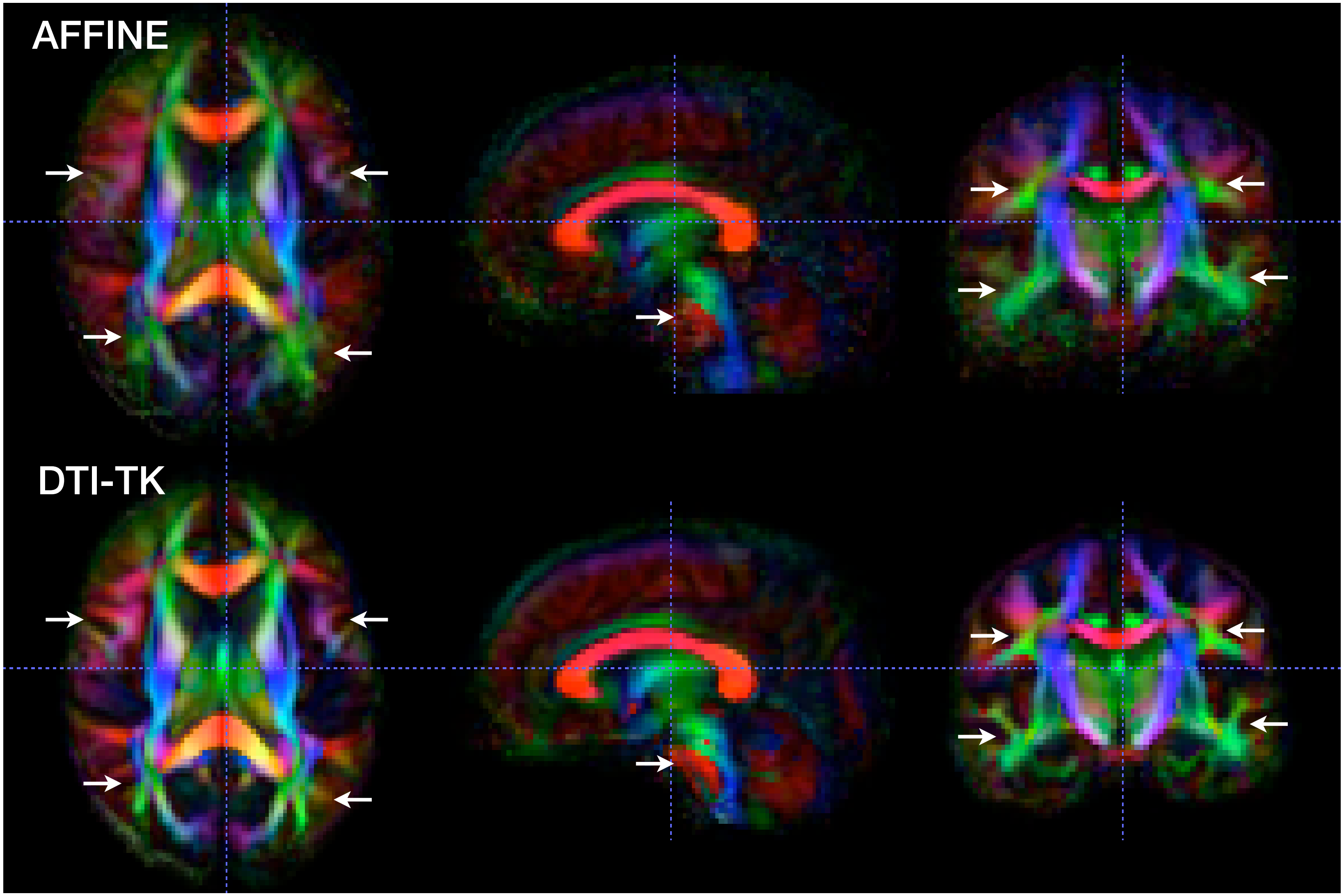


Guimond et al, CVIU 00

Zhang et al, MICCAI 07

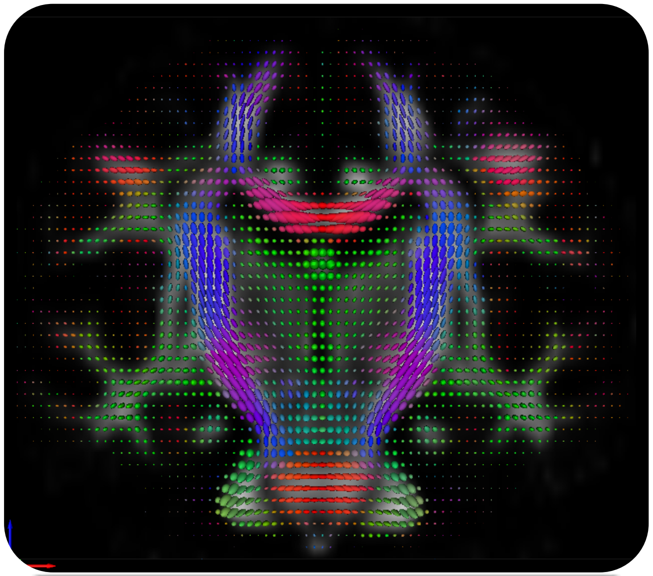
DTI-TK provides an implementation

Improved registration allows generation of better white matter atlases

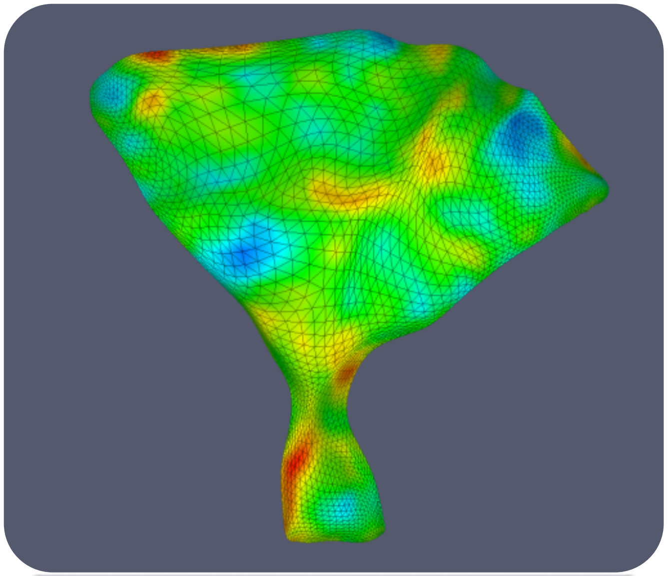


Zhang et al., WBIR 2010. White matter atlas of 51 older healthy adults

Outline

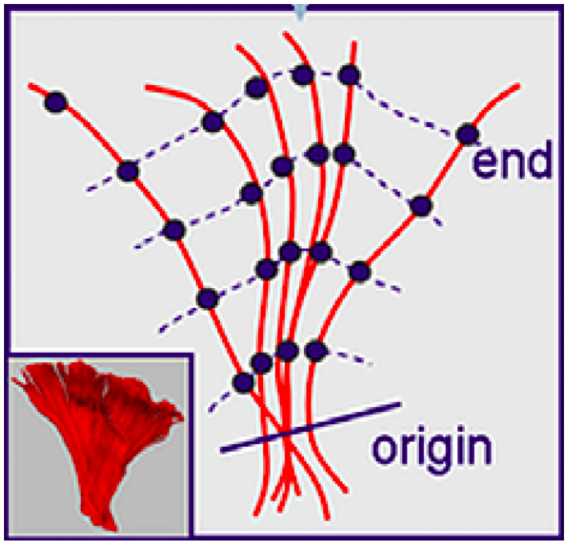


A specialized method for DTI registration and atlas-building

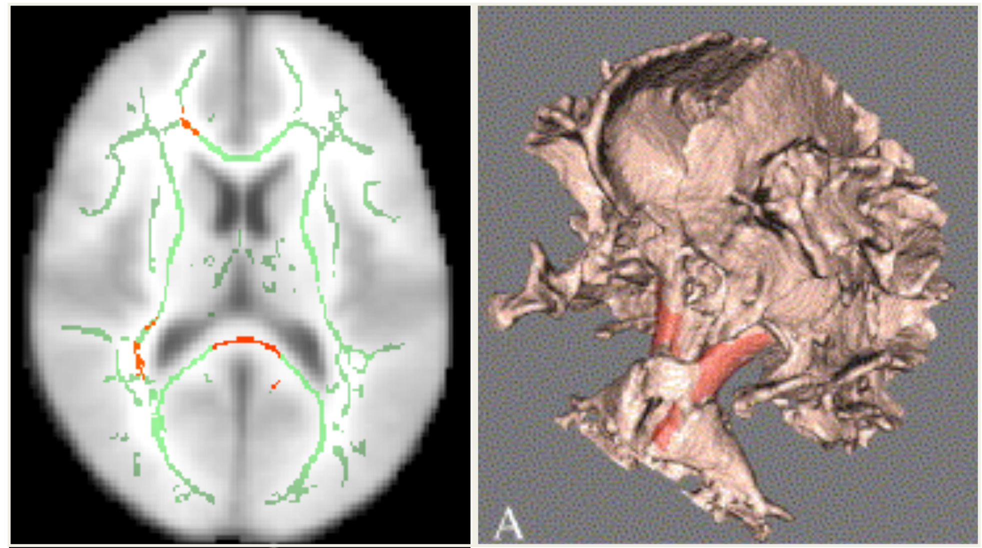


A surface-based framework for DTI population studies

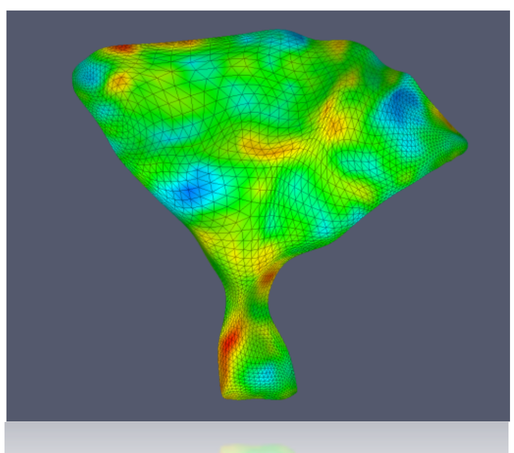
Tract-Specific Analysis (TSA):
at the intersection of two WM analysis paradigms



Curve-based tract representation
(e.g. Corouge et al., *MedIA*, '06)



TBSS: Skeleton-based white matter representation
(Smith et al., *Neuroimage*, '06)

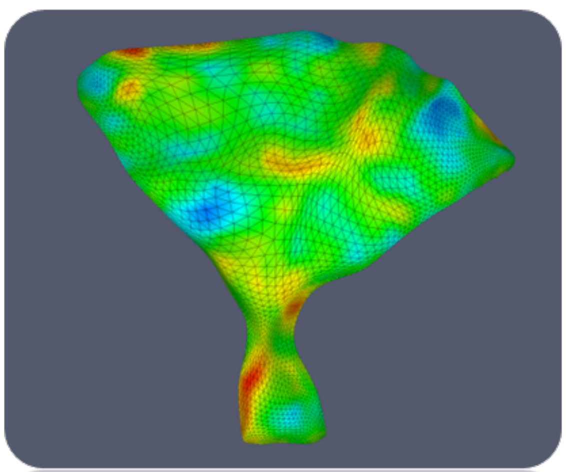


TSA Framework

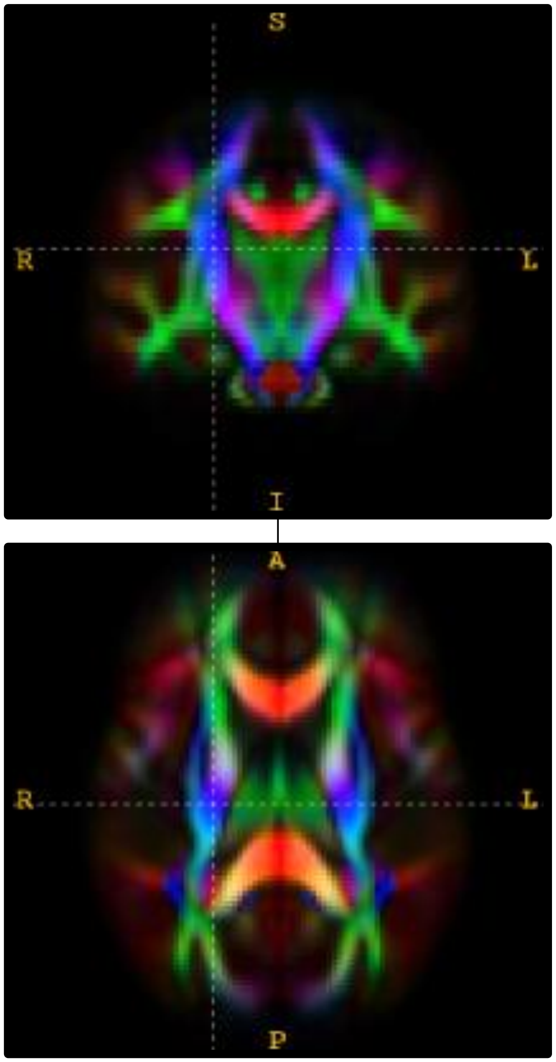
Normalization
- Population-Specific WM Atlas

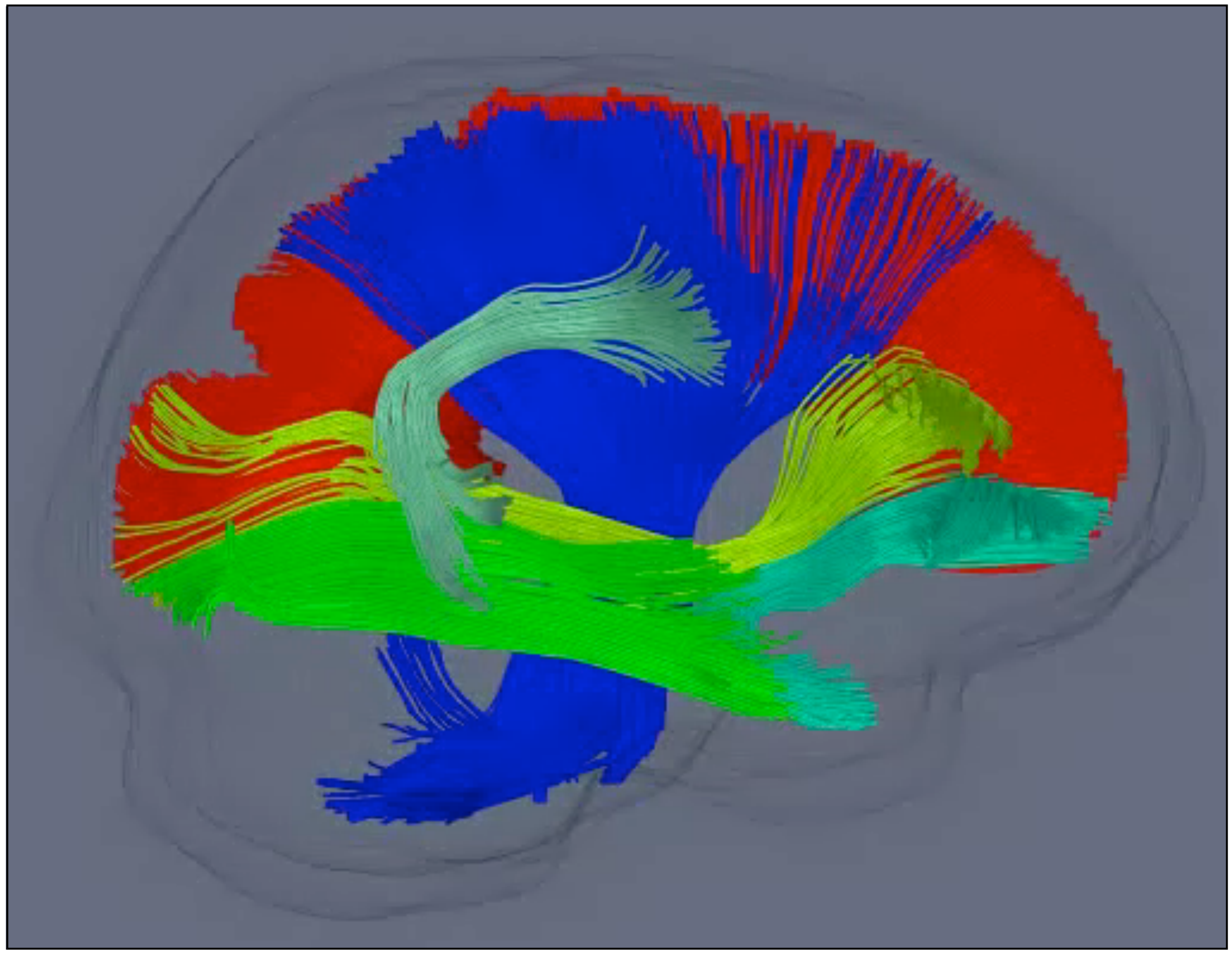
Fasciculus Segmentation
- Fiber tracking
- Track grouping and labeling

Surface-Based Modeling
- Representation via geometrical models
- Tract-Wise Statistical Mapping
- Visualization and Flattening



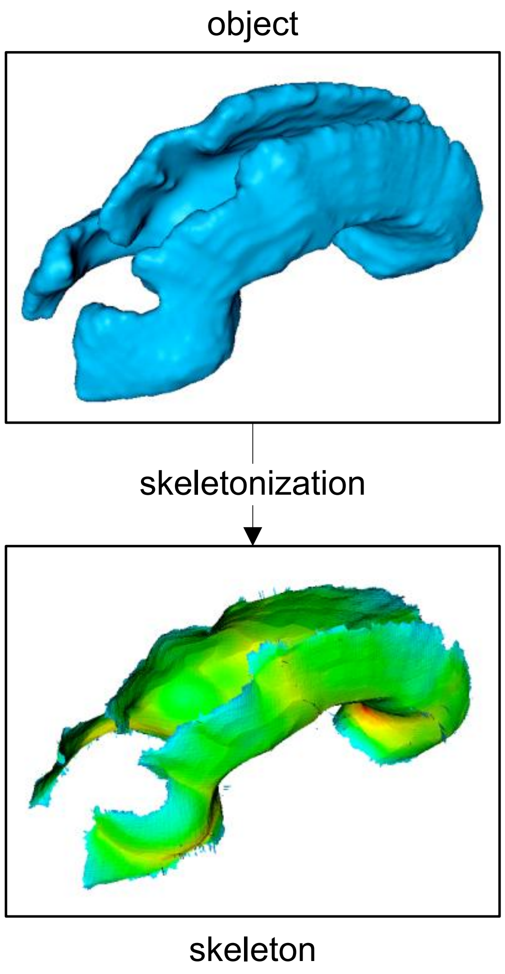
Normalization to common anatomical space enhances fiber tractography



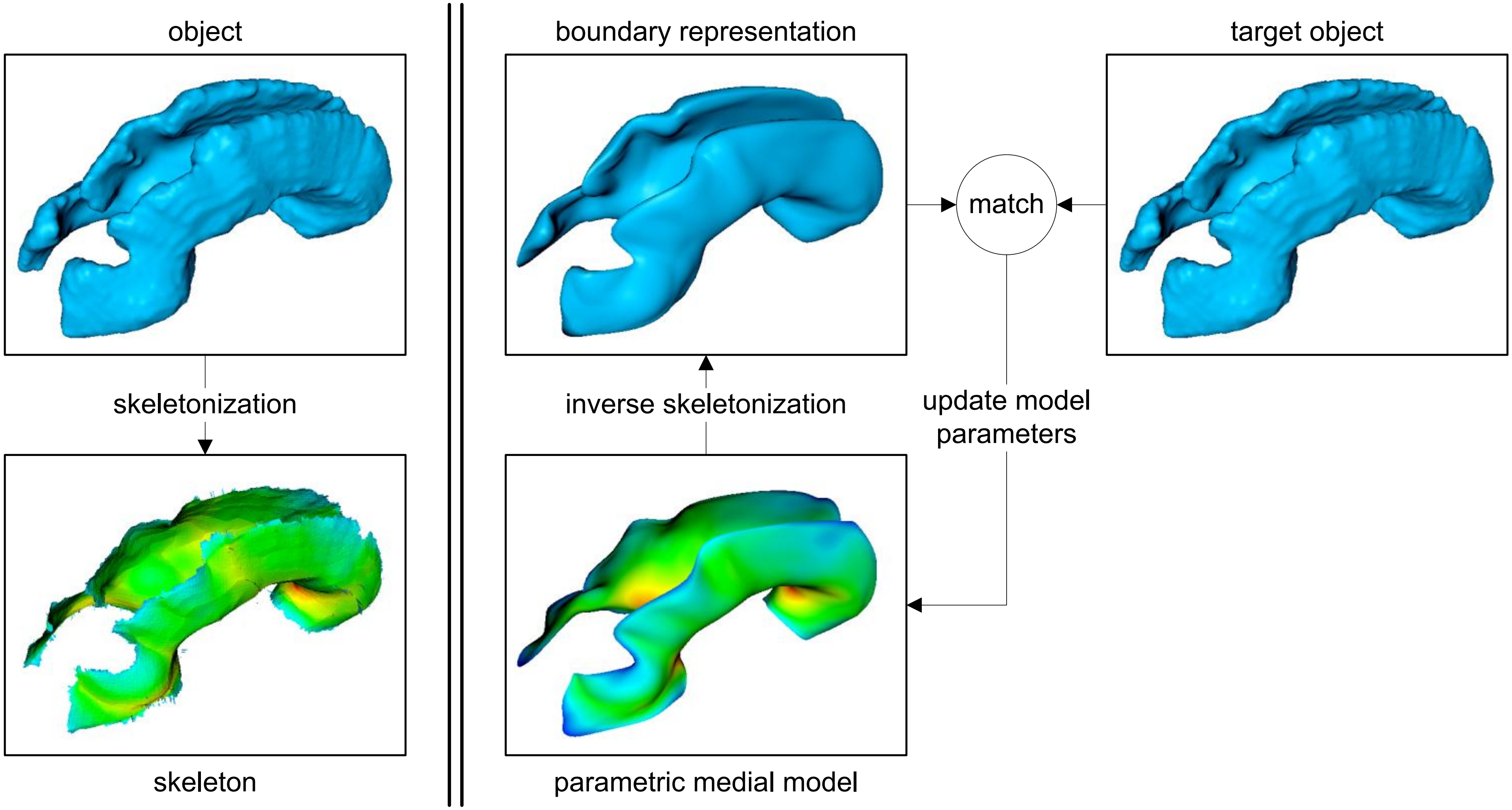


Segmentation via Deterministic Tractography, following Mori *et al.*, 2002; Wakana *et al.*, 2004

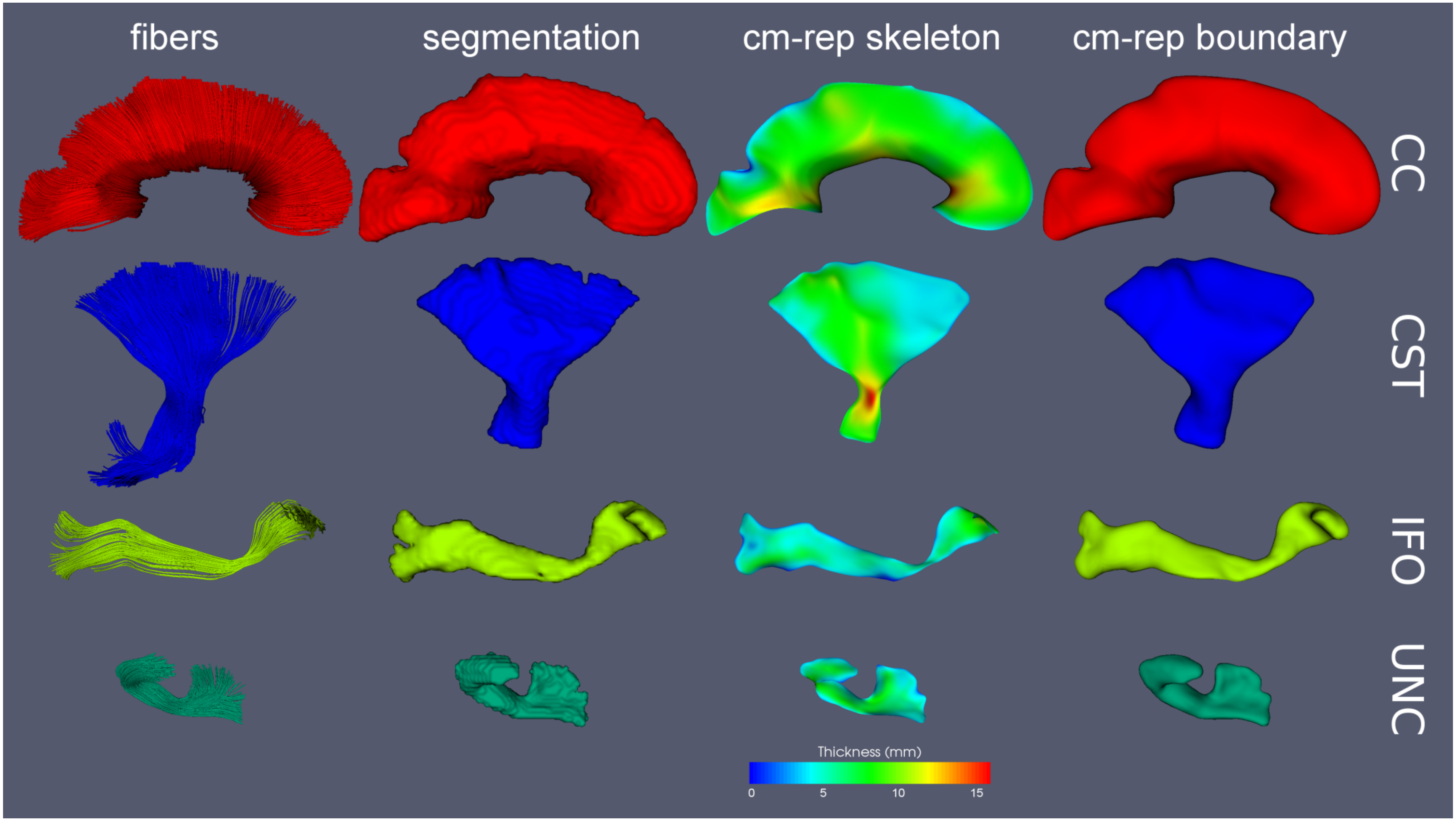
Deformable medial models are fitted to sheet-like white matter tracts



Deformable medial models are fitted to sheet-like white matter tracts



Surface-based modeling of major sheet-like tracts



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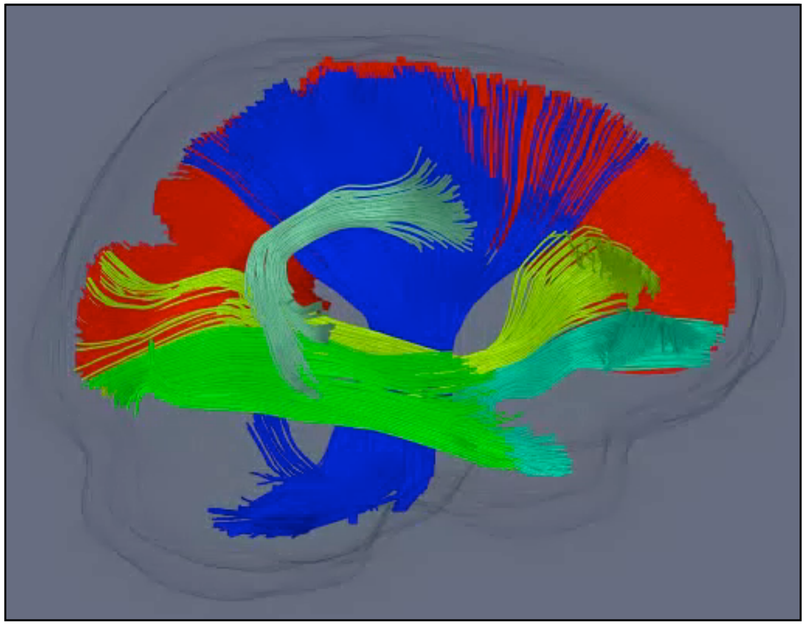
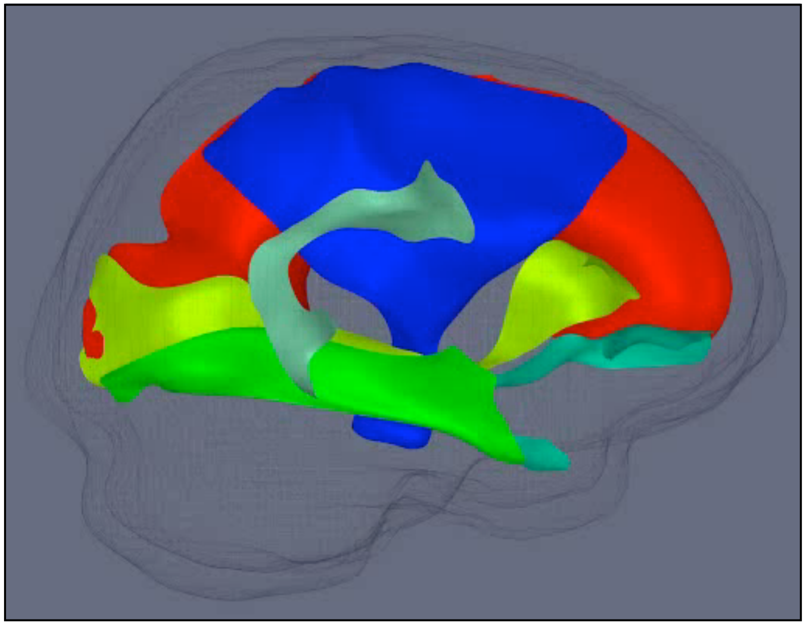
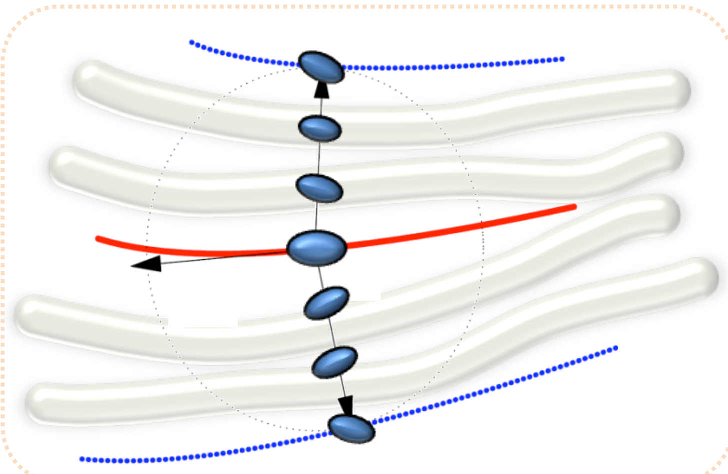


Six sheet-like fasciculi

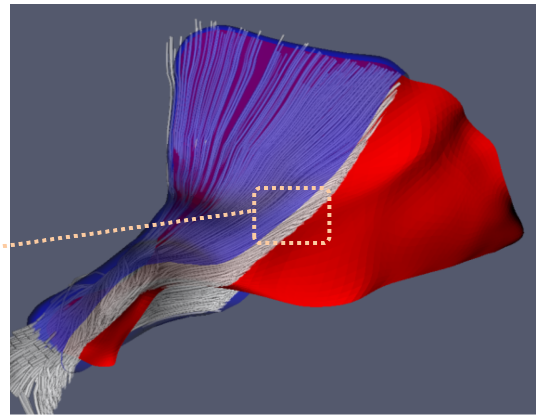


Surface representation

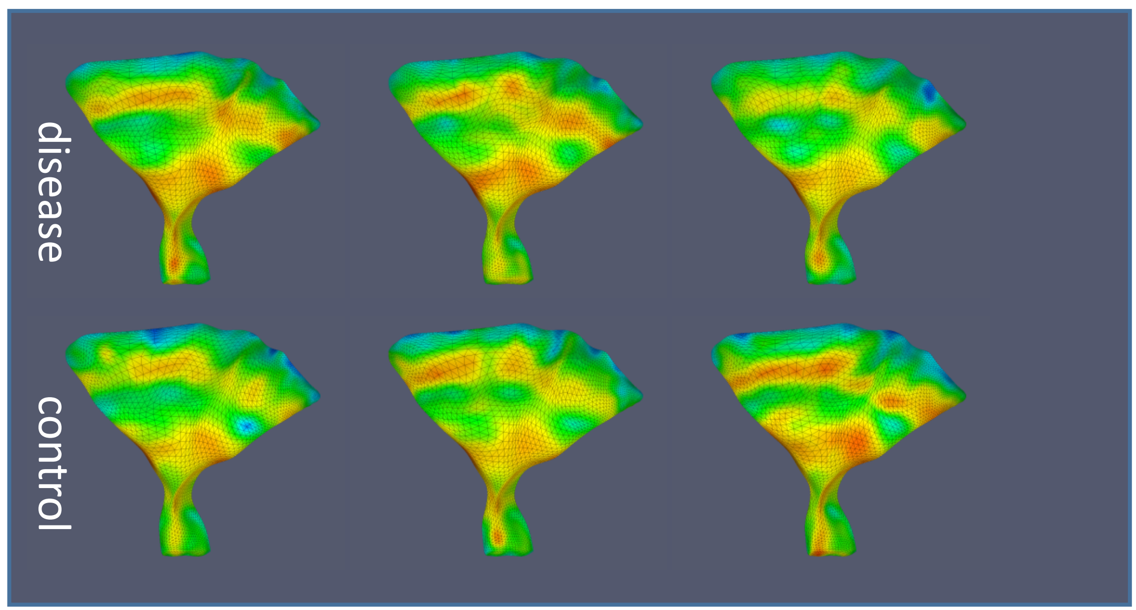
Tract-specific statistical inference



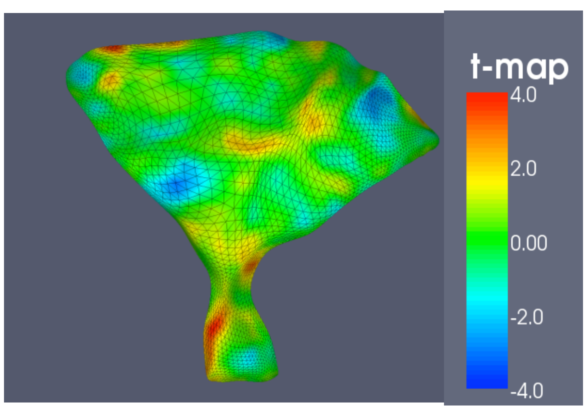
Dimensionality Reduction



Model and fibers

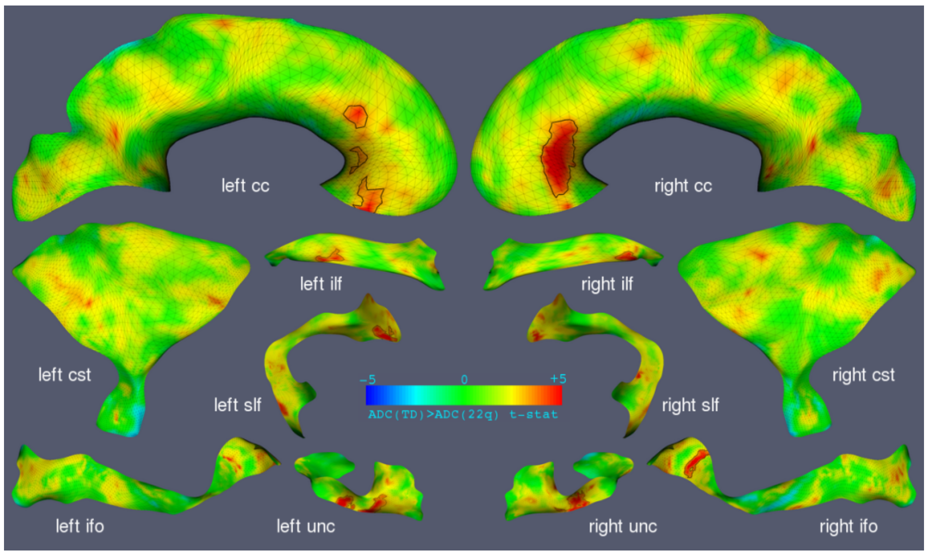


Subject FA Maps

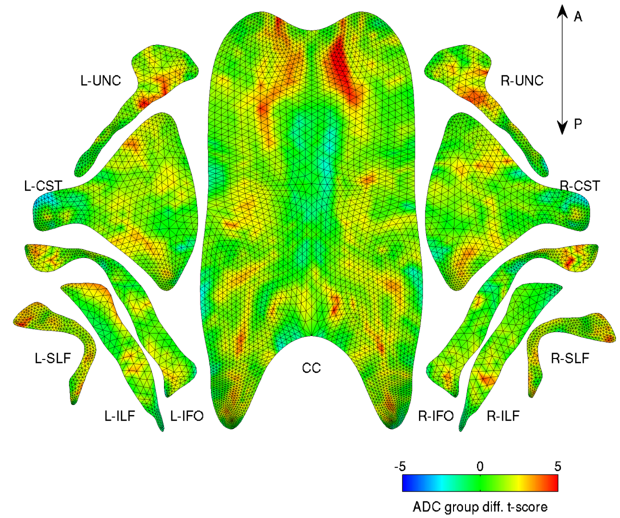


Tract-wise t-map

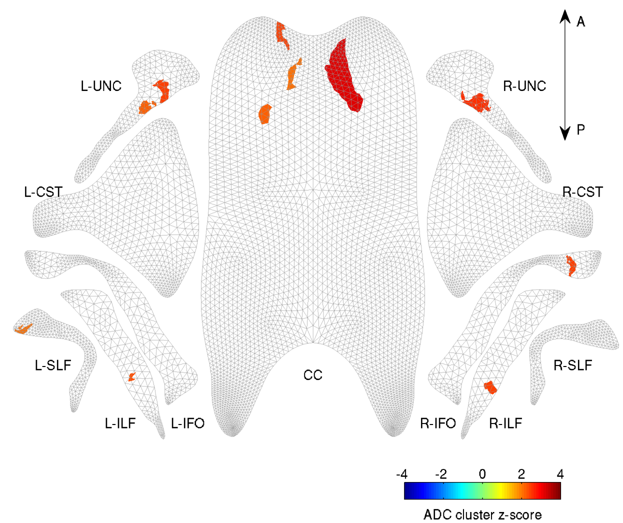
Parametric surface representation aids visualization



3D t-statistic map



2D t-statistic map

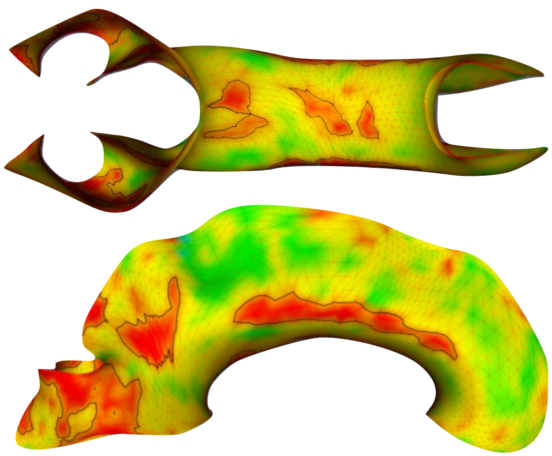


2D FWER-controlled cluster analysis

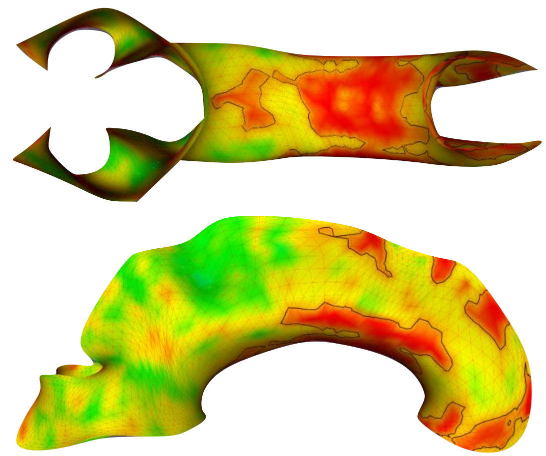
Results shown are ADC difference maps from a 22q11.2 deletion syndrome study (Tony J. Simon, PI)

TSA examples: white matter changes in AD/FTD (30-directional DW-MRI)

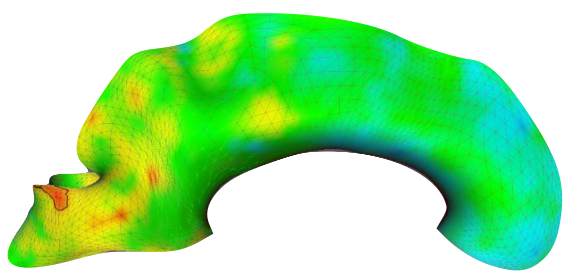
AD	23f / 21m	67.8 (10.9)
FTD	27f / 35m	66.5 (7.6)
CTL	16f / 8m	66.1 (8.8)



Reduced FA in AD vs. CTL

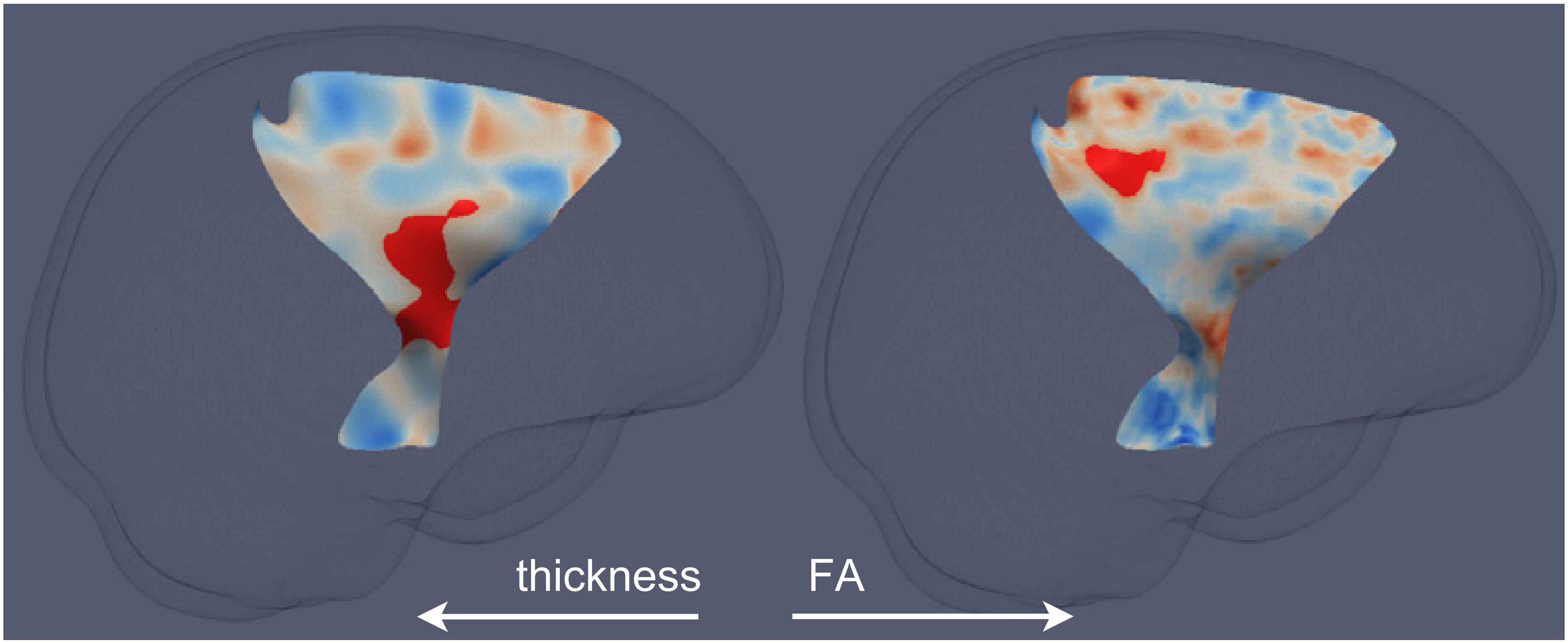


Reduced FA in FTD vs. CTL



Reduced FA in AD vs. FTD

Subject-space TSA: combined analysis of FA and thickness in ALS



Zhang et al., MedIA 2011

Conclusions

- Full tensor information should be used for DTI volume registration
- Tensor reorientation is required prior to tensor matching
- Population-specific atlases derived from DTI normalization allow excellent fiber tractography
- Surface-based representation of sheet-like tracts facilitates tract-specific statistical analysis
- All tools are part of free DTI-TK software

www.nitrc.org/projects/dtitk

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